IUL 2000

REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-00-

0309

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
00/7/1

3. REPORT TYPE AND DATES COVERED
Progress 00/2/15-00/7/1

4. TITLE AND SUBTITLE
(U) PDF Modelling of Turbulent Combustion

5. FUNDING NUMBERS
PE-61102F
PR-2308
SA-BS, G-F49620-97-1-0126

6. AUTHOR(S)
S.B. Pope

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Cornell University
Ithaca, NY 14853

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/NA
110 Duncan Ave, Suite B115
Bolling AFB
Washington, DC 20332-0001

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 Words)*

Significant progress was made in the application of PDF-based turbulent combustion models to the Sandia pilot-jet nonpremixed flames. These PDF calculations were described in two recent papers (Xu & Pope 2000 and Tang, Xu & Pope 2000) and they are summarized in this report. The first of these works showed that the PDF method is capable of describing, quantitatively, the phenomena of local extinction and reignition (as functions of jet velocity and axial distance) that are observed in these flames. The second paper extended the methodology to include radiative heat loss, and the calculation of NO_x.

20000720 044

14. SUBJECT TERMS
Turbulent Combustion

15. NUMBER OF PAGES
7

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

PDF MODELLING OF TURBULENT COMBUSTION

AROSR Grant F-49620-00-1-0171

Principal Investigator: Stephen B. Pope

Mechanical & Aerospace Engineering
Cornell University
Ithaca, NY 14853

SUMMARY

Significant progress was made in the application of PDF-based turbulent combustion models to the Sandia pilot-jet nonpremixed flames. These PDF calculations were described in two recent papers (Xu & Pope 2000 and Tang, Xu & Pope 2000) and they are summarized in this report. The first of these works showed that the PDF method is capable of describing, quantitatively, the phenomena of local extinction and reignition (as functions of jet velocity and axial distance) that are observed in these flames. The second paper extended the methodology to include radiative heat loss, and the calculation of NO_x.

PDF MODEL

The model is based on the transport equation for the joint probability density function of velocity, turbulence frequency and thermochemical composition. For the combustion of methane considered, the chemical kinetics are represented by the augmented reduced mechanism of Sung, Law & Chen (1998). Without NO_x chemistry (ARM1) there are 16 species; with NO_x there are 19. For computational tractability, the effects of reaction are implemented by the in situ adaptive tabulation (ISAT) algorithm (Pope 1997).

LOCAL EXTINCTION

The piloted jet nonpremixed flames measured by Barlow & Frank (1998) consist of a central jet of methane, a substantial annular pilot, and coflowing air. In the three flames considered, D, E and F, the jet velocities are U_J = 50, 74 and 99 m/s, respectively. The amount of local extinction increases with the jet velocity.

Figure 1 shows scatter plots of the CO_2 mass fraction against mixture fraction for Flame F at 30 jet radii downstream. In the measurements (left-hand figure), each point represents a laser shot: in the calculations (right-hand figure), each point represents a particle from the particle/mesh method used to solve the PDF equation. The upper curve is the composition of a mildly strained laminar flame. The fact that the bulk of the points lie beneath this line is an indication of local extinction. The lower curve is the conditional mean from the data. Good agreement between the calculations and the measurements may be observed.

Xu & Pope (2000) define a "burning index" (BI) as a measure of (the lack of) local extinction. To explain the definition of the burning index we again refer to Fig. 1.

The vertical dashed line shows a mixture fraction range around strichiometric (defined by Barlow & Frank 1998). The lower solid circle is the mean of the data points that lie in this range; whereas the upper solid circle is the value from the laminar flame. The burning index is defined as the ratio of these two values. Consequently, a burning index of 1 corresponds (roughly) to complete combustion, and 0 corresponds to complete extinction.

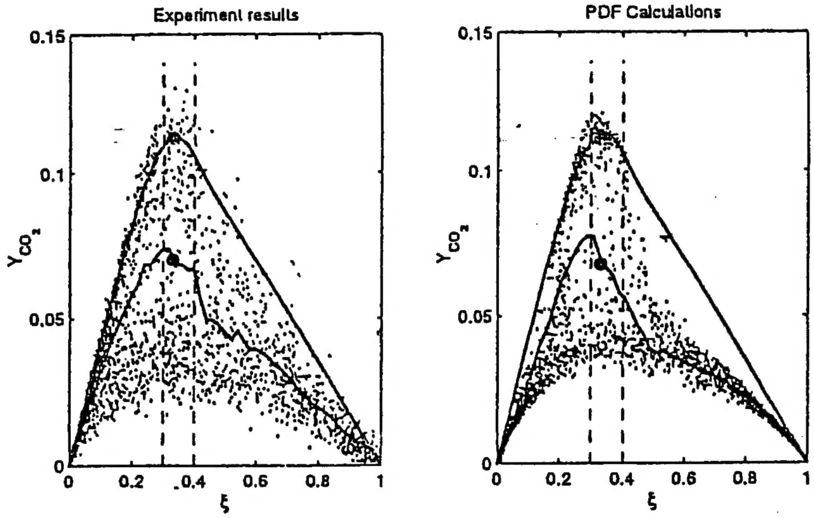

Figure 1: Scatter plots of CO_2 mass fraction against mixture fraction for flame F at an axial distance of 15 jet diameters. Left-hand plot, experimental data of Barlow & Frank (1998); right-hand plot, PDF calculations of Xu & Pope (2000).

Figure 2 compares the measured and calculated burning indexes of different species (and temperature) for all three flames as functions of axial distance. As may be seen, with few exceptions, the PDF calculations accurately describe the dependence of BI on both the jet velocity and on the axial distance. These results demonstrate a significant advance in our abilities to calculate substantial finite-rate chemistry-turbulence interactions.

MAJOR AND MINOR SPECIES

For flame D, Fig. 3 shows calculated radial profiles of the mean and r.m.s. of the NO mass fraction compared to the experimental data. Good agreement may be observed for both quantities, and the downstream evolution is well represented. It may be seen that radiative heat loss does not have a significant impact on NO (in this flame).

Figure 4 shows the conditional mean (conditioned on mixture fraction ξ) of various quantities. These conditional means provide a good indication of the accuracy of the chemistry calculations. As may be seen, the agreement between the calculations and the experiments is uniformly satisfactory. The trends of NO with jet velocity and downstream distance are accurately represented; and the accuracy of the CO calculations shows that ARM remedies previously observed discrepancies.

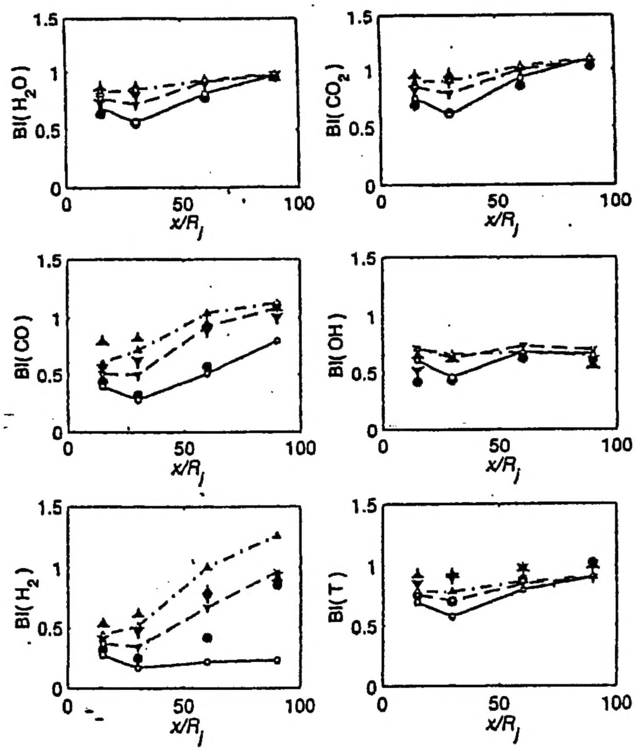

Figure 2: Burning indexes for flames D, E and F. Filled symbol: experiments; lines with empty symbols, PDF calculations. Circle and solid line, flame F; down-triangle and dashed line, flame E; up-triangle and dashed-dotted line, flame D. (From Xu & Pope 2000.)

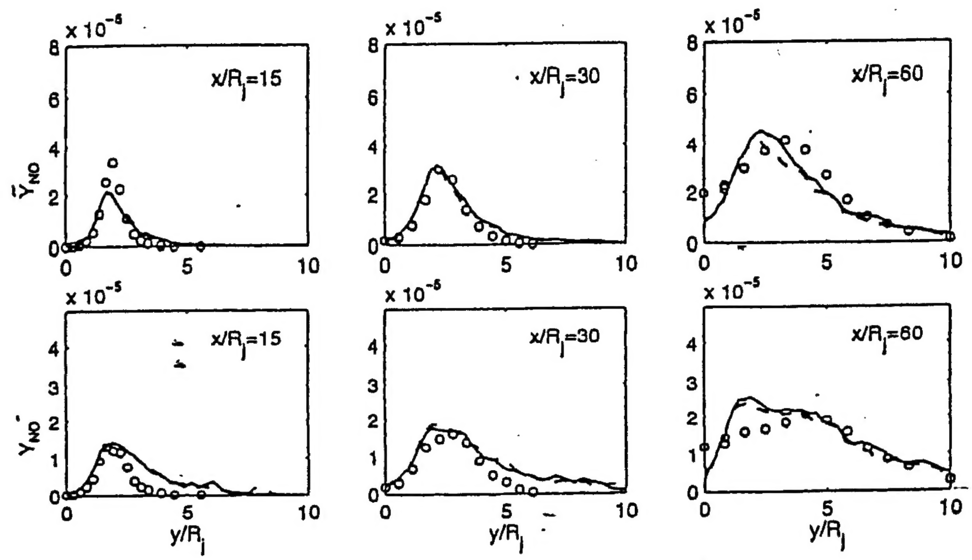

Figure 3: Radial profiles of the mean (upper plots) and r.m.s. (lower plots) of NO mass fraction in flame D. Symbols, experimental data (Barlow & Frank 1998); solid and dashed lines, PDF calculations without and with radiative heat loss. (From Tang, Xu & Pope 2000.)

REFERENCES

1. Barlow R.S. and Frank J.H. "Effects of turbulence on species mass fraction in methane/air jet flames," In *Twenty-seventh Symp. (Int'l) on Combust.,* page 1087, Pittsburgh, 1998. The Combustion Institute.

2. Pope S.B. (1997) "Computationally Efficient Implementation of Combustion Chemistry using In Situ Adaptive Tabulation," Combustion Theory and Modelling, **1**, 41–63.

3. Sung, C. J., Law C. K., and Chen J.-Y. (1998). "An augmented reduced mechanism for methane oxidation with comprehensive global parametric validation." In *Twenty-seventh Symp. (Int'l) on Combust.*, Pittsburgh, pp. 295–304. The Combustion Institute.

4. Tang Q., Xu J. and Pope S.B. (2000) "PDF calculations of local extinction and *NO* production in piloted-jet turbulent methane/air flames", Twenty-Eighth Symp. (Int'l) on Combust. (to be published).

5. Xu J. and Pope S.B. (2000) "PDF calculations of turbulent nonpremixed flames with local extinction," Combust. Flame (to be published).

PERSONNEL SUPPORTED

Prof. S.B. Pope, PI
S. Joseph, graduate student
Q. Tang, graduate student

DEGREES GRANTED

S. Joseph, M.S.

PUBLICATIONS

The following papers were written during the reporting period.

1. Q. Tang, J. Xu and S.B. Pope (2000) "PDF calculations of local extinction and NO production in piloted-jet turbulent methane/air flames," Twenty-Eighth Symp. (Int'l) on Combust. (to be published).

2. J. Xu and S.B. Pope (2000) "PDF calculations of turbulent nonpremixed flames with local extinction," Combust. Flame (to be published).

PRESENTATIONS

June 5, 2000—University of California, Santa Barbara, Institute of Theoretical Physics.

June 13, 2000—AFOSR/ARO Contractors' Meeting, Workshop presentation, Santa Fe, NM.

July 27, 2000—Fifth International Workshop on Nonpremixed Turbulent Combustion, Delft, Netherlands.

July 31, 2000—International Combustion Symposium, presentation.

OTHER INTERACTIONS

During the reporting period the PI has visited:

Rolls Royce Corporation, Indianapolis, IN
Rocketdyne, Canoga Park, CA
Los Alamos National Lab, NM

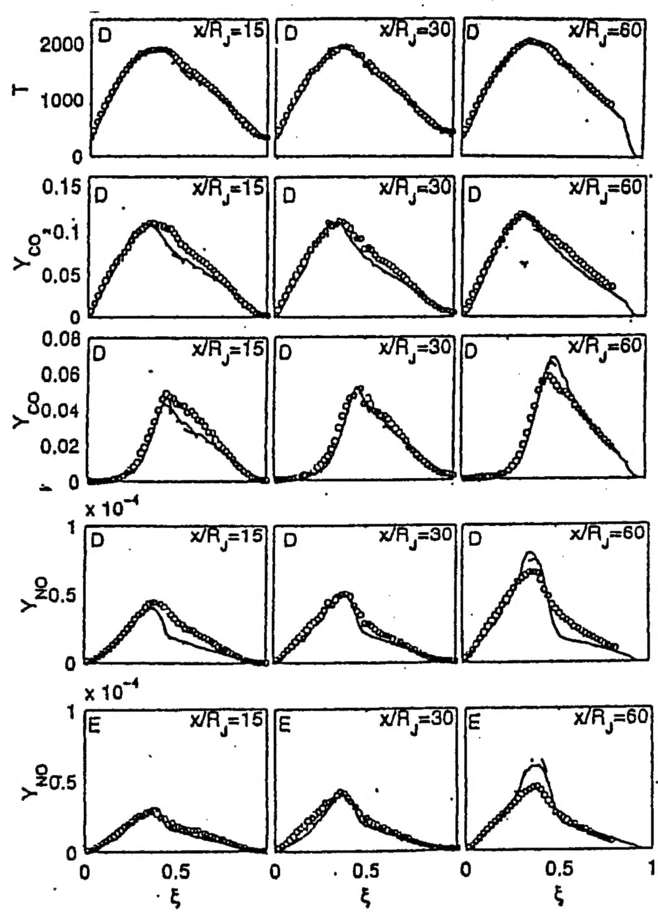

Figure 4: Conditional means in flames D and F. Lines and symbols as in Fig. 3.

Principal Investigator Annual Data Collection (PIADC) Survey Form

NOTE: If there is insufficient space on this survey to meet your data submissions, please submit additional data in the same format as identified below.

PI DATA

Name (Last, First, MI) Pope, Stephen B.

Institution Cornell University

Contract/Grant No F4962-00-1-0171

AFOSR USE ONLY
Project/Subarea ________/____

NX ________

FY ________

NUMBER OF CONTRACT/GRANT CO-INVESTIGATORS

Faculty 1 Post Doctorates 0 Graduate Students 1 Other 0

PUBLICATIONS RELATED TO AFOREMENTIONED CONTRACT/GRANT

NOTE: List names in the following format: Last Name, First Name, MI

Include: Articles in peer reviewed publications, journals, book chapters, and editorships of books

Do Not Include: Unreviewed proceedings and reports, abstracts, "Scientific American" type articles, or articles that are not primary reports of new data, and articles submitted or accepted for publication, but with a publication date outside the stated time frame

Name of Journal, Book, etc: None

Title of Article ________

Author(s) ________

Publisher (if applicable) ________

Volume ____ Page(s) ____ Month Published ____ Year Published: ____

Name of Journal, Book, etc ________

Title of Article ________

Author(s) ________

Publisher (if applicable) ________

Volume ____ Page(s) ____ Month Published ____ Year Published ____

HONORS/AWARDS RECEIVED DURING CONTRACT/GRANT LIFETIME

Include All honors and awards received during the lifetime of the contract or grant, and any life achievement honors such as (Nobel prize, honorary doctorates, and society fellowships) prior to this contract or grant.

Do Not Include: Honors and awards unrelated to the scientific field covered by the contract/grant.

Honor/Award Fellow, American Physical Society Year Received: 1991

Honor/Award Recipient(s) S.B. Pope

Awarding Organization American Physical Society

Associate Fellow 1984
S.B. Pope
AIAA

Overseas Fellow 1989
S.B. Pope
Churchill College, Cambridge